From Z-Machines to ALMA: (Sub)millimeter Spectroscopy of Galaxies
ASP Conference Series, Vol. TBD, 2006
A. J. Baker, J. Glenn, A. I. Harris, J. G. Mangum, and M. S. Yun, eds.

MUSYC: A Deep Square Degree Survey of the Formation and Evolution of Galaxies and Supermassive Black Holes

Eric Gawiser and the MUSYC Collaboration

NSF Astronomy & Astrophysics Postdoctoral Fellow (AAPF), Yale Astronomy Department and Yale Center for Astronomy & Astrophysics, PO Box 208101, New Haven, CT 06520-8101

Abstract. The Multiwavelength Survey by Yale-Chile (MUSYC) is optimized for the study of galaxies at $z = 3$, AGN demographics, and Galactic structure. MUSYC consists of deep optical (UBVRIz′) and near-infrared (JHK) imaging of four fields on the sky covering 1.2 square degrees to AB limiting depths of U,B,V,R=26 and K=22. Our optical catalog contains 277,341 objects detected in BVR images with median seeing of $0.9''$. Satellite coverage of our fields includes Chandra, XMM, GALEX, HST-ACS, and Spitzer, with the Extended Chandra Deep Field South imaged at all of these wavelengths plus the radio, making it the premier multiwavelength field on the sky. Detailed follow-up spectroscopy is being performed with VLT+VIMOS, Magellan+IMACS and Gemini+GNIRS. MUSYC provides ideal supporting data for surveys with Z-Machines and rich target lists for spectroscopy with ALMA. We are conducting a census of protogalaxies at redshift three (Lyman break galaxies, Lyman-alpha emitters, Distant red galaxies, Sub-millimeter galaxies and AGN) in order to separate physical properties from selection effects. We discuss measurements of the dark matter halo masses and halo occupation numbers of these populations and of the total cosmic star formation rate at z=3. MUSYC publications and data releases are available at http://www.astro.yale.edu/MUSYC.

1. Survey Design

The Multiwavelength Survey by Yale-Chile is unique for its combination of depth and total area, for providing the $UBVRIz'JHK$ photometry needed for high-quality photometric redshifts over 1.2 square degrees of sky, and for having additional coverage at X-ray, UV, mid- and far-infrared wavelengths. The primary goal is to study the properties and interrelations of galaxies at a single epoch corresponding to redshift ~ 3, using a range of selection techniques.

Lyman break galaxies at $z \simeq 3$ are selected through their dropout in U-band images combined with blue continuua typical of recent star formation at $\lambda > 1216$Å in the rest-frame (Steidel et al. 1996, 1999, 2003) detected in $BVRIz'$. Imaging depths of U,B,V,$R \simeq 26$ were chosen to detect the LBGs, whose luminosity function has a characteristic magnitude of $m_* = 24.5$ in $R_{\rm AB}$, and to find their Lyman break decrement in the U filter via colors $(U - V)_{AB} > 1.2$.

Lyman α emitters at $z \simeq 3$ are selected through additional deep narrow-band imaging using a 50Å fwhm filter centered at 5000Å. These objects can be detected in narrow-band imaging and spectroscopy by their emission lines,

allowing us to probe to much dimmer continuum magnitudes than possible for Lyman break galaxies.

It has recently become clear that optical selection methods do not provide a full census of the galaxy population at $z \sim 3$, as they miss objects which are faint in the rest-frame ultraviolet (Franx et al. 2003; Daddi et al. 2004). With this in mind, MUSYC has a comprehensive near-infrared imaging campaign. The NIR imaging comprises two components: a wide survey covering the full square degree and a deep survey of the central $10' \times 10'$ of each field. The 5σ point source sensitivities of the wide and deep components are $K_{s,AB} = 22.0$ and $K_{s,AB} = 23.3$ respectively. NIR imaging over the full survey area provides a critical complement to optical imaging for breaking degeneracies in photometric redshifts and modeling star formation histories. Deeper JHK_s imaging over $10' \times 10'$ subfields opens up an additional window into the $z \simeq 3$ universe as the $J - K$ selection technique (Franx et al. 2003; van Dokkum et al. 2003, 2004, 2006) are used to find evolved optically-red galaxies at $2 < z < 4$ through their rest-frame Balmer/4000Å break.

In addition to the optical and near-infrared, imaging campaigns at other wavelengths and follow-up spectroscopy are integral parts of MUSYC. X-ray selection is used to study AGN demographics over the full range of accessible redshifts, $0 < z < 6$, (see Lira et al. 2004) with Spitzer imaging used to detect optically- and X-ray-obscured AGN (Treister et al. 2004; Lacy et al. 2004). This also allows a census of accreting black holes at $z \simeq 3$ in the same fields to study correlations between black hole accretion and galaxy properties at this epoch.

Multiple epochs of optical imaging are being used to conduct a proper motion survey to find white dwarfs and brown dwarfs in order to study Galactic structure and the local Initial Mass Function (see Altmann et al. 2005).

The four survey fields (see Table 1) were chosen to have extremely low reddening, H I column density (Burstein & Heiles 1978), and 100μm dust emission (Schlegel, Finkbeiner, & Davis 1998). Additionally, each field satisfies all of the following criteria: minimal bright foreground sources in the optical and radio, high Galactic latitude ($|b| > 30$) to reduce stellar density, and accessibility from observatories located in Chile. The survey fields will be a natural choice for future observations with ALMA.

Table 1. MUSYC Survey Fields and their Galactic extinction, 100μm emission and neutral hydrogen column densities.

Field	RA [J2000]	DEC [J2000]	E(B-V)	100 μm Emission [MJy/Sr]	N_H [10^{20} cm^{-2}]
ECDF-S	03:32:29.0	-27:48:47	0.01	0.40	0.9
SDSS1030+05	10:30:27.1	+05:24:55	0.02	1.01	2.3
CW1255+01	12:55:40.0	+01:07:00	0.02	0.81	1.6
EHDF-S	22:32:35.6	-60:47:12	0.03	1.37	1.6

Table 2. MUSYC optically-selected catalogs and imaging depths (5σ point source detection in AB magnitudes). Depths in JHK are for deep central $10' \times 10'$ regions in each field, with the surrounding areas covered to about one magnitude shallower.

Field	U	B	V	R	I	z′	J	H	K	NB5000
ECDF-S	26.0	26.9	26.4	26.4	24.6	23.6	24.3	23.8	23.4	25.5
SDSS1030+05	25.8	26.0	26.2	26.0	25.4	23.7	24.1	23.9	23.3	24.8
CW1255+01	26.0	26.2	26.1	26.0	25.0	24.1	24.0	22.8	23.0	24.4
EHDF-S	26.0	26.1	26.0	25.8	24.7	23.6	24.3	23.4	23.4	24.1

2. Results

The data reduction and photometry methods used to generate optically-selected catalogs are described by Gawiser et al. (2006a). The corrected aperture (APCORR) fluxes yield the optimal point source detection depths listed in Table 2 for the 277,341 objects in our optical catalog covering 1.2 square degrees.

Our color selection and clustering analysis of Lyman break galaxies (LBGs) is described by Gawiser et al. (2006a), and our color selection and stellar population analysis of Lyman alpha emitting galaxies (LAEs) is described by Gawiser et al. (2006b). Figure 1 shows the redshift distributions measured from MUSYC spectroscopy with Magellan+IMACS.

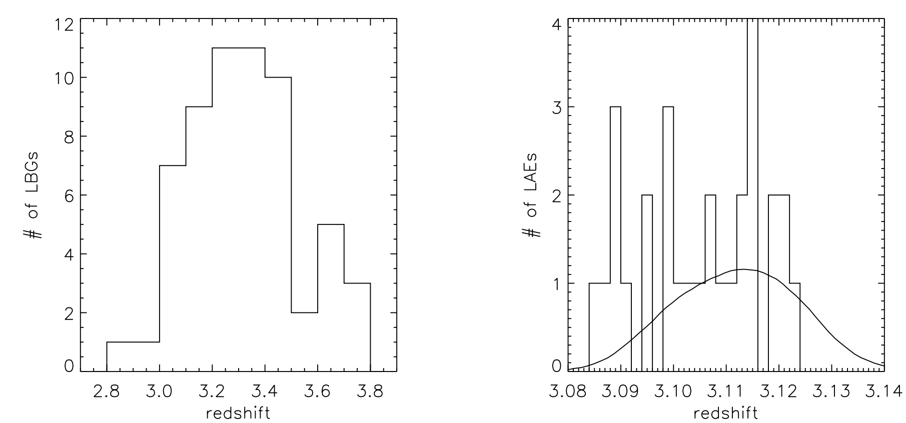

Figure 1. Histograms of redshifts for 60 Lyman break galaxies (left panel) and 29 Lyman Alpha Emitting galaxies (right panel). The solid curve in the right panel shows the expected redshift distribution calculated by convolving the filter response with the observed equivalent width distribution.

The total cosmic star formation rate density supplied by spectroscopically confirmed populations at $z = 3$ is 0.2 $M_\odot$ yr^{-1} Mpc^{-3}. Lyman break galaxies only supply half of this, with most of the rest supplied by Distant Red

Galaxies (Webb et al. 2006), Sub-millimeter Galaxies (Chapman et al. 2005) and Damped Lyman α Absorbers (Wolfe, Gawiser, & Prochaska 2003; for a review, see Wolfe, Gawiser, & Prochaska 2005).

Preliminary results of our clustering analysis imply that LBGs have a halo occupation number close to 1 i.e. each available dark matter halo with mass above $3 \times 10^{11} M_\odot$ contains one LBG. However, AGN and LAEs have halo occupation numbers around 0.1 i.e. only one in ten dark matter halos in the mass range hosting these objects are actually found to contain one of them. This implies that the duty cycles for active accretion onto supermassive black holes and for dust-free star formation in these objects are roughly 10%. All measured protogalaxy families are found to have dark matter halo masses of at least $10^{11} M_\odot$ (Gawiser 2005), implying that galaxy formation may have been suppressed sufficiently in typical (unbiased) dark matter halos ($10^9 M_\odot$ at $z = 3$) to remove them from observed samples.

Acknowledgments. We thank the organizers for running an enjoyable and educational workshop and the editors for their hard work assembling this volume. This material is based upon work supported by the National Science Foundation under Grant. No. AST-0201667, an NSF Astronomy and Astrophysics Postdoctoral Fellowship (AAPF) awarded to E.G.

References

Altmann, M., Méndez, R. A., Ruiz, M.-T., van Altena, W., Gawiser, E., Maza, J., & van Dokkum, P. 2005, in ASP Conf. Ser. 334: 14th European Workshop on White Dwarfs, ed. D. Koester & S. Moehler, 143

Burstein, D. & Heiles, C. 1978, ApJ, 225, 40

Chapman, S. C., Blain, A. W., Smail, I., & Ivison, R. J. 2005, ApJ, 622, 772

Daddi, E. et al. 2004, ApJ, 600, L127

Franx, M. et al. 2003, ApJ, 587, L79

Gawiser, E. 2005, to appear in New Horizons in Astronomy, ASP Conference Series, astro-ph/0512384

Gawiser, E. et al. 2006a, ApJS, 162, 1

—. 2006b, submitted to ApJ Letters

Lacy, M. et al. 2004, ApJS, 154, 166

Lira, P. et al. 2004, in IAU Symposium, ed. T. Storchi-Bergmann, L. C. Ho, & H. R. Schmitt, 531–532

Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525

Steidel, C. C., Adelberger, K. L., Giavalisco, M., Dickinson, M., & Pettini, M. 1999, ApJ, 519, 1

Steidel, C. C., Adelberger, K. L., Shapley, A. E., Pettini, M., Dickinson, M., & Giavalisco, M. 2003, ApJ, 592, 728

Steidel, C. C., Giavalisco, M., Pettini, M., Dickinson, M., & Adelberger, K. L. 1996, ApJ, 462, L17

Treister, E. et al. 2004, ApJ, 616, 123

van Dokkum, P. G. et al. 2003, ApJ, 587, L83

—. 2004, ApJ, 611, 703

—. 2006, ApJ, 638, L59

Webb, T. M. A. et al. 2006, ApJ, 636, L17

Wolfe, A. M., Gawiser, E., & Prochaska, J. X. 2003, ApJ, 593, 235

—. 2005, ARA&A, 43, 861